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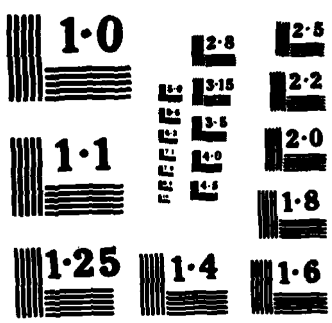
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Applying a Qualitative Modeling Shell to Process Diagnosis: The Caster System

by

Timothy F. Thompson and William J. Clancey

Department of Computer Science

Stanford University
Stanford, CA 94305

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REMOVING THE KNOWLEDGE BASE FROM A MEDICAL DIAGNOSIS SYSTEM, BUT RETAINING THE DIAGNOSTIC PROCEDURE, LED TO A REUSABLE EXPERT SYSTEM SHELL. THIS PAPER EVALUATES AN APPLICATION TO SANDCASTING.

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Applying a Qualitative Modeling Shell to Process Diagnosis: The Caster System

by

Timothy F. Thompson, Westinghouse R&D Center

William J. Clancey, Stanford University

Stanford Knowledge Systems Laboratory
Department of Computer Science
701 Welch Road, Building C
Palo Alto, CA 94304

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The purpose of knowledge engineering is to develop partial qualitative models for solving practical problems. These models--called knowledge bases in expert systems--must have appropriate diagnostic knowledge to deal with the real-world problems.

In general, solutions to diagnostic problems can be either selected from a set of pre-enumerated alternatives (for known conditions) or constructed (for novel problems or those that combine multiple, interacting disorders in an unforeseen way). While engineering design is often thought of as a constructive problem-solving process, diagnosis is typically thought of as a selection or classification problem. But the solution method is not inherent in the task itself. Instead, it depends on the problem solver's previous knowledge, requirements for customization, and the like.

For example, engineering design may involve selection from among competing possible designs (especially in the case of the experienced designer), and diagnosis sometimes requires consideration of the system's structure and function. ~~[6]~~

Nevertheless, useful programs can be developed that solve diagnostic problems by selection alone. We believe that starting with a well-defined classification procedure and a relational language for stating the classification model eases the development of a program that diagnoses by selection. To test this thesis, we built an expert system, called Caster, that addresses a particular diagnostic problem: malfunctions in industrial sandcasting. Our goal was to demonstrate that these control structures, developed for a medical diagnosis problem, are general and applicable to engineering applications.

Caster uses the Heracles qualitative modeling environment, a shell generalized from the Neomycin medical diagnosis system. Heracles provides a well-defined diagnostic

procedure that structures inference according to a pattern called heuristic classification, and it provides a relational language to state knowledge of taxonomies of malfunctions and abnormal state transitions. [5]

History

The Mycin system, [11] developed in the mid-1970s, showed that it was possible for a computer to diagnose and treat infectious diseases with the accuracy of a human expert. [2] Subsequent research has sought to improve understanding of the nature of domain knowledge and the expert's inference process. One line of research resulted in Neomycin, a reconfigured and extended version of the original Mycin system. [4]

Neomycin's principled representation of domain knowledge is in terms of disease taxonomies, causal networks of abnormal states, and hierarchies of findings such as measurements, general observations, and disease symptoms. Its design also explicitly represents control strategy so that the system can articulate its diagnostic strategy to users, and so that, in a tutorial setting, the system has some basis for recognizing the logic behind student behavior. [4]

Consequently, Neomycin's knowledge base consists of both domain-level rules about medical disorders and control rules that express techniques to select and apply domain rules as human experts would. For efficiency, these control rules can be precompiled into procedural code and can be interpreted by an explanation facility to teach the system's diagnostic strategy.

Neomycin's control knowledge (a rule set that heuristically classifies findings,

abnormal states, and diseases) evolved concurrently with its domain-specific knowledge base. The set of control rules developed for Neomycin has evolved into a cohesive whole characterized as heuristic classification. Knowledge engineers have used this control strategy in several expert systems, including Mycin, Puff, Sacon, the Drilling Advisor, Grundy, and Sophie III. The strategy was *not* explicitly represented, so the systems could not reason about their actions.

This is the crucial difference between Heracles and, for example, Emycin, which does not have a heuristic classification control strategy built in. Thus, Emycin users implicitly build a heuristic classification control strategy into their domain rules, and every system designer (knowledge engineer) must repeat this task. Clearly, this is a significant obstacle to efficient knowledge acquisition -- one Heracles can overcome.

Heuristic classification

Simple classification problem-solving involves selecting from a set of pre-enumerated solutions. These solutions are often organized hierarchically, and classification consists of matching observations about an unknown entity against features of known solutions.

In heuristic classification, solutions and solution features may be matched *heuristically*, by direct, nonhierarchical association with some concept in *another* classification hierarchy. For example, Mycin does more than identify an unknown organism in terms of visible features of an organism: Mycin heuristically relates an abstract characterization of the patient to a classification of diseases.

Figure 1 shows the inference structure schematically. It shows that heuristic

classification consists, essentially, of data abstraction, heuristic match, and hypothesis refinement. Basic observations about the target system are abstracted into feature categories according to definitional relationships, qualitative relationships between numeric measurements and nonnumeric conceptual descriptions, and generalizations between classes of findings and their subtypes.

Inferential leap. From this hierarchy of data abstractions, the heuristic classification problem solver makes a great inferential leap via heuristic or causal relations to a hierarchy of solution classes. A heuristic relation is uncertain, often derived empirically from the problem solver's (such as a physician's) experience.

A heuristic relation typically takes the place of a network of causal relations between problem features and solutions because the causal relations are unobservable, poorly understood, or invariant for most cases. After a heuristic match or causal propagation suggests a general malfunction hypothesis, the hypothesis must be refined according to the distinctions relevant to fixing the target problem (that is, prescribing therapy).

Refinement goal. The goal of refinement is to confirm or rule out competing specializations of the general hypothesis at each level in the malfunction taxonomy by requesting specific findings or tests. The result of this refinement is the specific cause of the general malfunction.

For example, if a heuristic match suggests a general hypothesis (solution class), a heuristic classification system begins to explore and refine the classification by replacing the hypothesis on the system's current list of potential malfunctions (called the differential) with known subtypes. The system tries to gather more evidence to confirm

or rule out each competing hypothesis. The system repeats the refinement phase for each subtype.

The classification hierarchies are not always trees, as generally portrayed for simplicity in this article. They may be "tangled" structures with some concepts having multiple parents. While it is convenient to think of heuristic classification as ordered steps of data abstraction, heuristic match, and hypothesis refinement, the heuristic classification model actually makes no claims about the execution order.

Depending on the needs of the application, the diagnostic procedure can be organized to reason, for example, either forward from observations to solutions or backward by hypothesizing solutions and then asking for findings that either confirm or refute the hypotheses.

The heuristic classification strategy implemented in Heracles is opportunistic: The system pursues lines of reasoning as they are suggested by new findings. The system simply does not do all the data abstraction, then all the heuristic matching, and then all the hypothesis refinement. Instead, the refinement process may suggest the need for new data (to confirm or refute a hypothesis), which in turn might trigger further data abstraction, and so on.

Heracles shell

The Heracles system is a comprehensive environment for building heuristic-classification qualitative models of engineering problems. This environment includes an explanation facility, [7] an interactive, graphics-based display developed for debugging

and teaching, [10] and a graphics-based knowledge editor designed for the Caster system.

These facilities give the knowledge engineer a well-defined relational language to express knowledge about classes of solutions and their features and specializations, about classes of findings, and about networks of causal relationships among abnormal states.

We generalized Heracles from Neomycin the same way Emycin was generalized from Mycin. [12] We removed all the domain rules and domain parameters from Neomycin and generalized any references to medicine in the control rules. Figure 2 shows Heracles as the core of the Neomycin and Caster systems. The relational language for qualitative models is the same. The classification procedure indexes the model in terms of these relations.

Implementing classification. Part of the key to efficient model design for selection problems is having a heuristic-classification control strategy already built into the problem solver. If the knowledge engineer can solve a problem with this computational method -- and experience shows it to be extremely general -- his job will be much easier because the vocabulary for stating the qualitative model and the procedure for interpreting it during a consultation are supplied in advance. The knowledge engineer is thus freed to concentrate on defining the basic terms and their relationships in the target domain.

In Heracles, control rules are grouped into tasks like explore-and-refine a general hypothesis, group-and-differentiate the current hypotheses in the differential, process a

(new) finding, and so on. There are 29 tasks and 75 control rules. (These control rules are also referred to as metarules since they are essentially rules which reason about the application of domain-specific rules or, more generally, what information to gather, and what assertions to make.)

Each task is associated with a short, ordered set of control rules. These rules are often applied iteratively according to the specification of the given task. Thus, heuristic classification in Heracles is highly structured and has relatively few steps or methods to achieve any one task.

Figure 3 shows an example of one of the control rules Heracles uses to process input data. Roughly translated, it says, "If the current task is forward-reason, and if a newly entered piece of data has not yet been clarified, then invoke a subtask called clarify-finding to further classify the data."

For example, if Neomycin learns that the patient has a headache, one of the possible choices it has is to ask more specific questions (such as how long, how often, or exactly where these headaches occur) that further clarify the initial, general finding of headache.

It is exactly this collection of tasks and metarules developed in Neomycin that we use in Caster, although not all of them apply. For instance, those rules pertaining to the distinction between circumstantial evidence and laboratory data are superfluous in Caster because all the data in Caster is circumstantial.

Knowledge-expression language. Another part of the key to efficient model design for selection problems is a well-defined relational language in which the knowledge

engineer can express knowledge of the domain. In Heracles, the fundamental terms (domain parameters) include findings, descriptions of abnormal internal occurrences (for simplicity we will call them states), and treatable causes. The fundamental relations include heuristic rules expressing a cause and effect (or causal) relationship, subsumption relations, taxonomic relations, and qualitative abstraction rules.

The possible relations between domain parameters that we need to describe the Caster system are as follows. Findings can subsume other findings (for example, since brain surgery is "a kind of" surgery, surgery is said to subsume brain surgery). Likewise, abnormal states can subsume other abnormal states. Abnormal processes are grouped into a classification hierarchy of diagnostic hypotheses by links that express a type/subtype or taxonomic relationship.

Findings and diagnostic hypotheses may be related directly by heuristic rules or by causal networks of abnormal states. Thus, findings can be caused by abnormal states, abnormal states can be caused by other abnormal states, and abnormal states can be caused by a particular hypothesized malfunction in a class of malfunctions. In general, diagnostic hypotheses are types of malfunctions endemic to a specific domain.

In our specific application of heuristic classification to diagnosis of processes, the disorder classification models the process in terms of what can go wrong at particular stages. Each terminal node specifies a model of the world in terms of symptoms and causes, and each terminal node exists because it is a treatable cause (that is, it can be heuristically related to fixes).

Moreover, each fix is a change to physical system functions and processes. Thus, our

goal is to construct a qualitative model that will fix a physical system, not a model that diagnoses a system for its own sake.

Tools to express knowledge. The ability to efficiently build a useful knowledge base partly depends on the well-known expert system tenets: The interface should be easy to learn, and easy to use. The Heracles user interface has a graphics-based display facility and a graphics-based knowledge editor. The editor is mouse- and window-driven, and its main menu is displayed as a pop-up window that lets the knowledge engineer move a node, add a node, delete a node, add a link, or delete a link (see Figure 4).

Nodes correspond to domain parameters such as findings, abnormal states, and malfunctions. Links refer to relations between parameters, such as causal rules, subtype relations, and subsumption relations.

An important feature of the knowledge editor is its knowledge of which domain parameters can be associated by which relations. For example, there are a number of slots associated with causal rules, and each slot may take any of a number of values. The knowledge engineer must only specify nodes and links between them -- the knowledge editor will determine which slots and values are appropriate, and then fill them in automatically.

Thus, the knowledge engineer doesn't have to know how to fill all the appropriate slots in all the appropriate schemata each time he specifies a domain relation. He doesn't even have to know that these slots exist. The knowledge editor makes the job of entering new knowledge much easier. It also makes it easier for the knowledge engineer

to see, literally, how the changes he makes will affect the old knowledge.

Sandcasting domain

Sandcasting is a metalworking process used to make all sorts of objects from crescent wrenches to V8 engine blocks to ocean liner propellers. It involves packing a two-part box, called a flask, full of sand around a pattern of the object to be cast. In Figure 5, the casting is of an L-shaped object. The pattern is removed by separating the box along a parting line. The dimensions of the flask can be from about a foot square to 20 or 30 feet square, depending on the size of the object to be cast.

Molten metal is poured down a large tapered hole, called a sprue, into a cavity, called a sprue well, that cuts down on the turbulence caused by pouring and that allows impurities to settle before flowing into the mold cavity. The metal flows into the mold through runners that open onto the mold through gates.

The placement and size of the pattern equipment -- sprues, runners, and gates -- is critically important. For example, if the gates are too small, the metal may not fill the mold before beginning to solidify, thus cutting off flow into the mold prematurely. On the other hand, if the gates are too large, impurities can wash into the mold, causing structural and surface defects, like cracks and bubbles, in the casting. There are also many other considerations in pattern equipment design.

As the metal cools, its volume is reduced because molten metal has more volume than solid metal. As the metal solidifies, it must be kept under pressure and more molten metal must be available to replace the lost volume. Other funnel-shaped holes called

risers, which fill with metal during pouring, take care of this. The force of gravity on the metal in the risers can exert enough pressure to keep the casting from developing shrinkage cracks.

This qualitative physical description of sandcasting forms the foundation to understand the techniques in diagnosing sandcasting malfunctions. The problem is how to get a computer to understand sandcasting so that it can diagnose malfunctions.

The malfunctions we intend Caster to diagnose are the common and repeatable failures the quality control engineer faces every day. For example, the temperature of the molten metal, the pattern equipment, and the molding sand can vary from casting to casting. The pattern equipment will gradually wear away with time. The molding sand may contain varying amounts of moisture. Levels of impurities in the molten metal will vary. All these variables and many more will cause repeatable sandcasting malfunctions.

Knowledge acquisition experiment

The knowledge bases for most expert systems depend very heavily on substantial input from domain experts. Unfortunately, the time of the skilled diagnostician is usually in great demand, so the time needed to build a quality knowledge base clashes with the need to have the expert fight fires elsewhere at the same time.

On the other hand, reference material for a given domain is often readily available -- but it is generally recognized that written references are a poor substitute for the domain expert.

Because the demand for the domain expert's time will always exceed the time available and because domain experts frequently consult reference works with good results, a fruitful research area would be trying to improve domain-knowledge acquisition techniques for written reference material.

Firmly entrenched procedure. One important reason an expert can assimilate new knowledge from reference manuals is that he starts with a firmly entrenched problem-solving procedure and a solid understanding of the fundamental terms and relations in his domain. We hypothesized that if we could equip a novice in the domain with a well-defined problem-solving procedure and a relational language for the knowledge representation, perhaps he, too, could efficiently construct a qualitative model of the domain from written reference materials.

Earlier research in studying a variety of knowledge bases, which showed that heuristic classification is a robust and well-defined problem-solving strategy for selection problems, seemed to endorse this hypothesis. Furthermore, there is considerable psychological support for heuristic classification as a model of how experts use experiential knowledge of familiar problem situations and solutions. [5]

To test our hypothesis, we chose an experiment in knowledge acquisition where we attempted to become, in a limited sense, our own domain experts by studying many textbooks and manuals on diagnosing sandcasting malfunctions, rather than extensively interviewing experts.

We tried to use heuristic classification and Heracles's relational model language as the foundation for our own emerging mental qualitative model, and as a framework to

guide the instantiation of Caster's computer model. We relied heavily on the casting handbook *Analysis of Casting Defects* [1] and referred to experts only on difficult or unclear matters.

Developing a qualitative model. There are about 15 major classes of sandcasting malfunctions. We initially concentrated on the kinds of sandcasting malfunctions that cause shrinkage cavities. A shrinkage cavity is the result of letting the casting cool without forcing new metal into the mold to offset the reduction in volume as the metal solidifies.

A shrink is an observable defect that would be considered a general finding in Caster as much as a headache is a finding in Neomycin. It is then possible to clarify that finding according to how long it has been occurring, what percentage of castings exhibit this defect, and the like.

Original plan. In our original plan, after establishing the data abstraction hierarchy for shrinks, the next goal was to identify from the manual the abnormal processes that could cause a shrink and then to organize them into a classification hierarchy with general malfunctions at the top and more specific malfunctions further down.

Finally, we wanted to uncover the heuristic relations between the data abstraction hierarchy and the taxonomy of malfunctions or perhaps identify a causal network of abnormal states relating abstractions and malfunctions.

In retrospect, we might have expected the job would not be so straightforward. Although we came to the task well-armed with our explicitly represented diagnostic procedure and relational model language, the authors of the casting manual didn't have

the same commitment to explicit diagnostic models.

Each sentence's mention of causality of some sort obscured problem feature hierarchies and malfunction taxonomies. The manual consists largely of independent heuristic causal relationships between observations and diagnoses. For example, the manual has many sentences like "Excessive gas producing inorganic materials can cause gas defects in castings . . . ," "Uncured shell sand will . . . cause pinholes," and "Excess moisture in green molding sand is probably the greatest cause of gas defects in cast metals."

Thus, this casting manual is loosely organized as a very long list of causal relations of the form <some malfunction> causes <some symptom>. This long list is subdivided into about 15 major sections corresponding to the major observable symptoms. Each section is divided into several subsections corresponding to the basic processes in which malfunctions arise.

General diagnostic strategy. The authors of the manual made no attempt to teach a general diagnostic strategy, probably because the assumed reader is one already skilled in the art of sandcasting diagnosis. By assuming that the reader is a sandcasting expert with his own well-developed diagnostic methods, the authors were free to provide useful reference information in a highly concentrated form that the reader can assimilate into his existing "knowledge base" as he sees fit.

Our first pass at representing this type of description resulted in a group of fragmented causal associations (see Figure 6). About all we were sure of was that shrinkage cavities were caused by a variety of problems, including inadequate supply, not enough gates and risers, risers that are too small, and gates that are too large. From

this sort of description, it was not at all obvious what were treatable causes, what were internal descriptions, and so forth.

Fundamental cause. However, after much reflection and several abortive attempts at restructuring our initial list of causal associations, we realized that a fundamental cause of shrinkage cavities was inadequate supply and that the other problems mentioned, like too few gates or risers, were causes of inadequate supply.

There are essentially three reasons why the casting might be inadequately fed. One is that there simply is no metal available to feed. This can result from too few risers, risers that are too small, and similar reasons. Another cause is that the mold broke, possibly due to mishandling. Thus, the metal was available but leaked out. The third cause is that the feed is shut off, possibly because the neck of the riser is too small (that is, the metal in the small riser neck solidified, preventing an adequate flow) or the metal was not heated sufficiently.

It should be clear that we were doing more than merely translating the text in the manual into Heracles's relational model language. In studying the manual, our own qualitative model of the shrinkage cavity problem gradually emerged. Only after we really understood the causality behind shrinks could we put that knowledge in the language used by Heracles.

At the same time, however, we used the causal structure defined by Heracles to enable us to ferret out the causal networks of abnormal state transitions implicitly expressed in the casting manual.

Another important insight was the realization that the general malfunction classes in

Neomycin are fundamentally different than those found in the sandcasting domain. In medicine, we see clearly identifiable abnormal processes (such as infectious processes, vascular disorders, and traumatic processes) and abnormal agents that cause those processes. In casting, there are no analogous abnormal processes or agents. Instead, there is a clear sequence of normal processes (such as melting, pouring, and solidifying) that are affected by abnormal events (such as a mold breaking or the feed being shut off).

Partial model. Figure 7 shows a simplified version of our reorganized knowledge of shrinkage cavities which shows the normal processes of melting, molding, solidifying, and so forth, with the abnormal conditions that might occur in each process. For example, a poor jacket fit is just one abnormal condition which might arise during the normal molding process.

Because we had difficulty with our first attempt at building a qualitative model for shrinkage cavities, and because we believed we had resolved the source of that problem, we continued developing knowledge of another common type of casting malfunction: gas defects (see in Figure 8).

Significantly, it took several man-months to come to grips with the shrinkage cavities model while it took only a couple of weeks to develop a similarly complex model for gas defects.

Example session. The following is an excerpt of a script (annotated in italics) showing heuristic classification as applied to the partial qualitative model shown in Figure 7.

```
16-May-85 22:43:56
 ------CASTING-4------
Please enter information about the casting
1) Casting Type:
IRON
2) Please describe the chief complaints:
** SHRINKAGE-CAVITIES
**
```

Caster begins by applying the heuristic rule suggesting inadequate supply.

```
DIFFERENTIAL: (INADEQUATE-SUPPLY 800)
```

Caster is exploring and refining the differential. Inadequate-supply has been replaced by metal-leak, feed-is-shut-off, and no-metal-to-feed. Metal-leak suggests a broken-mold, so Caster inquires whether there is evidence of a runout.

```
3) Does Casting-4 have a runout?
** N
```

Caster has looked at feed-is-shut-off, which suggests that fillets may be too small, so the system asks if the shrink is at a corner, which would be strong evidence for fillets-too-small.

```
4) Does Casting-4 have a shrink at a corner?
** Y
```

Finally, Caster looks for evidence that there is no metal available to feed, namely that there is a high reject ratio.

```
5) Does Casting-4 have a high reject ratio?
** N
DIFFERENTIAL: (METAL-LEAK 100) (FEED-IS-SHUT-OFF 100)
(FILLETS-TOO-SMALL 700)
```

This example shows how heuristic classification can reduce the amount of search required by ruling out some lines of reasoning while at the same time promoting a more focused and therefore more natural interaction with the user. The example also illustrates hypothesis refinement and the opportunistic style in which heuristic classification is implemented.

Inadequate-supply is replaced in the differential by its three children, metal-leak, feed-is-shut-off, and no-metal-to-feed. Each of these more specific hypotheses suggests hypotheses elsewhere in the malfunction taxonomy. Caster adds those hypotheses to the differential and tries to explore them along with the subtypes already in the differential by asking for confirming evidence which could in turn trigger further data abstraction. (Their children do not come into play in this example, and are therefore not shown in Figure 7.)

The next step in our development of Caster would be to extend and validate Caster's domain knowledge by using the system in the context of real-world problems. We are ready to perform such an analysis, but because the foundry has only very recently begun recording malfunction case histories, we cannot yet get the required data.

Experts examining traces of Caster working on hypothetical cases confirm that Caster does appear to make the correct diagnoses. This is important to us since one of our goals was to determine how well heuristic classification can be applied to nonmedical domains requiring causal reasoning.

Observations on the experiment. Although virtually all the well-known knowledge acquisition systems are designed specifically for human knowledge sources, we were able to show that Heracles, using an explicitly implemented heuristic classification control strategy and a relational language for building qualitative models, can build partial qualitative models for the sandcasting domain from diagnostic manuals.

Novice sandcasting diagnosticians such as ourselves could succeed in building Caster because the Heracles framework helped us understand the domain by organizing the

knowledge in the reference manuals so it could be used for diagnosis. Without it, we would still be staring at our original, overwhelming, unconnected, and not very useful list of causal relations from the manual.

The casting manual told us a lot of things about the casting domain, but it didn't tell us what to do with this knowledge. It didn't explain that some observations subsume other observations. It didn't explain that general malfunction classes can be refined into more specific hypotheses by asking specific questions. Heracles provided this vocabulary.

After we realized that sandcasting diagnoses are best characterized as a sequence of normal processes affected by abnormal events, we were able to use the casting manual efficiently to build partial qualitative models to diagnose sandcasting problems.

Understanding the different ways diagnostic hierarchies of processes can be organized is an important result of this research. For example, notice that the normal processes of sandcasting are subject to a temporal ordering. First we design the pattern, then build the mold, and then melt and pour the metal. Finally the metal solidifies.

A problem may occur in one process (a mistake in pattern design) but a symptom may not appear until several processes later (a shrinkage cavity). This provides a simple diagnostic heuristic we could add to Heracles -- moving from right to left in the tree of disorders (or backwards in time from effects to causes). This heuristic very nicely shows how the representation for causal processes relates to the diagnostic control rules.

Knowledge acquisition heuristics

Expert system researchers have reached the point of focusing less on "How do we build expert systems?" and more on "How do we build expert systems right?" For example, how do we design expert systems that can be better maintained, that can explain their reasoning to users, and that are easier to build?

Caster's purpose was less to demonstrate that we could build the system than it was to understand how starting with a relational vocabulary for a qualitative model influences knowledge acquisition. One result was the identification of knowledge acquisition heuristics that are new precisely because they view knowledge acquisition in terms of constructing a qualitative model.

These heuristics apply not only to diagnostic systems but also to qualitative modeling for design, modification, monitoring, and control of physical systems in general. These knowledge acquisition heuristics extend and refine the crucial questions Buchanan et al. [8] list: "What are the important terms and their interrelations? What does a solution look like and what concepts are used in it? How are objects in the domain related?" Indeed, these are crucial questions. However, identifying these questions is not nearly as difficult as answering them.

We used Heracles's relational language to help us identify the fundamental terms and relations in sandcasting. We identified the important substances in our domain, including molding sand, water, various gases, and iron. We identified the important processes that act on these substances, including melting metal, designing a pattern, building a mold, and pouring the metal.

We constructed classification hierarchies for each of these substances to define the causes of abnormal events that disrupt these normal processes. We identified high-level descriptions of the symptoms of these problems and then constructed abstraction hierarchies for each by considering the possible types of information characterizing each general finding. (That is, we looked for generalizations, definitions, and qualitative abstractions yielding the general findings.)

The last step was determining the heuristic relationships between elements of the data abstraction hierarchy and the malfunction taxonomy. Relating general classes, instead of specific findings and hypotheses, aids learning because many specific relations can be understood as special cases of a general rule.

Thus, the hierarchical structure of domain knowledge -- the categorization of processes, substances, and the like promoted by the heuristic classification model -- is especially beneficial to knowledge acquisition.

Step-by-step procedures. Our experience with Caster further shows that this step-by-step procedure for qualitative model building is generically applicable to selection problems:

- Describe abnormal events in terms of the overall stages of the manufacturing process.

Ease the categorization of processes and abnormal events by classifying abnormal events in terms of the processes they occur in. For example, the problem of inadequate supply occurs during the solidification process. A broken mold is the result of a flaw in the molding process.

- Identify abnormal properties of substances -- then look for causes.

Before thinking about causality, think of all the possible manifestations of a type of problem, and then establish causes. For example, metal contamination is a serious problem in casting. There are a number of possible contaminants, including aluminum, silicon, and phosphorus. After identifying as many contamination problems as possible, consider how each type of contamination might occur and how the problem would manifest itself. This method is much easier and more complete than trying to identify the many causes of metal contamination without first considering what those contaminants might be.

- Identify possible malfunctions, determine the corrections for those problems, and then translate those relationships to causality.

Perhaps using case histories. figure out what action is needed to fix each malfunction and translate that knowledge into a causal representation. For instance, for the feed shut-off problem, we ask what possible changes could remedy the situation. The answers include making the gates bigger, the neck of the riser bigger, the fillets larger, and the metal hotter. All these corrections appear in the causal model for shrinkage cavities shown in Figure 7.

- Establish causality between findings and malfunctions, then expand intermediate levels.

After establishing a causal chain between findings and malfunctions, go back and look for additional hidden causality between the links in the chain. We found that it is quite natural for the expert to leave out levels of causality because he knows the domain. This was frequently the case in the casting manual. By making implicit relations explicit

(as measured by need in actual cases), knowledge can be organized to use search-saving strategies such as explore-and-refine.

- Express causality in, for example, natural language first, then translate it to an expert system's format.

Start by ignoring the expert system entirely and concentrate on expressing causality in a convenient way. Insisting that the knowledge engineer express his rules in a particular expert system's format risks paralyzing the engineer with unnecessary and orthogonal analysis of issues of little concern to him at the moment.

The Caster knowledge-base editor made this even easier. It very naturally expresses parameters and the relationships between them without getting bogged down with unnecessary implementation details. The system implementation should be as transparent as possible to the knowledge engineer (and we expect this would be especially important for the domain expert).

Knowledge acquisition bottleneck

Many expert system researchers over the past 10 to 15 years have rallied behind the battle cry "Knowledge is power!" The prototypical expert system architecture emphasizes a simple inference engine that manipulates data in a knowledge base consisting of declarative rules and facts. The central idea is that the programmer is freed, by coding knowledge as declarative rules, from the constraints imposed by more traditional software languages. The programmer need not worry about each rule's context because the inference mechanism applies a rule only when its preconditions are satisfied.

This approach works in small domains but is very inefficient in real-world-scale applications. The two main problems are how does the system figure out which rules are applicable and which of those rules does it apply first?

As a result, virtually all large-scale expert systems either embed control knowledge in the domain knowledge or make the simple inference engine more complex. Often, the two approaches are mixed.

In either case, the burden of organizing system knowledge for efficient and correct use falls on the person who creates and maintains the knowledge base: the knowledge engineer. This job is extremely difficult, and the inability to encode knowledge representations except through this slow process is often referred to as the knowledge acquisition bottleneck.

There is widespread belief in artificial intelligence circles that this is the last nut to crack -- then expert systems will truly flourish in the commercial world.

However, one might argue that this intuition is overly simplistic -- what's really happening is that all the problems associated with traditional programming have been pushed onto the knowledge engineer. The Mycin system, for example, depended heavily on the skill of the knowledge engineer, who coded (in an unobvious and implicit way) virtually all the structure and strategies for using domain knowledge. [3]

As another example, most OPS5-based systems, like R1, [9] use some domain rules only to create purely contextual assertions that control the application of other rules. The basic idea is to partition the domain into a large number of small subproblems so only a limited number of rules need to be considered at any one time. Again, the

burden is on the knowledge engineer to organize domain knowledge so that this partitioning is possible.

Thus, the knowledge engineer who builds knowledge bases for real-world expert system applications is still programming in very much the traditional sense of the word. In fact, his job is now even harder, both because he has to implement control strategies in languages that don't explicitly support control constructs and because people now expect his software to solve more difficult problems.

Thus, an expert system is by no means a software panacea. Someone, somewhere, has to do the difficult job of organizing domain knowledge efficiently to handle the target application correctly. Whether this organization is implemented in a standard procedural program or by a knowledge engineer in an expert system's rule base, it is a difficult and expensive job.

The central problem is that typical knowledge bases consist of both partial qualitative models and embedded inference procedures. We conclude that if control knowledge recurs in various domains, as it does in problems solved by experiential classification knowledge, distilling that knowledge and stating it explicitly once saves considerable effort.

Put another way, constructing useful models is a fundamental concern for most engineering problems. Knowledge engineering specifically concerns the construction of qualitative models. However, the dictum "Knowledge is power" doesn't discriminate between the model of the domain and the inference procedure. Thus, the relation of this new technique to traditional engineering practice is not as clear as it could be.

The inference procedure of heuristic classification supplied with Heracles reduces knowledge acquisition to constructing classification and state-transition qualitative models. Since the inference procedure is general, the power of the knowledge lies in the store of previously encountered problem situations and solutions and of heuristic connections between them.

Therefore, we believe the lessons of knowledge engineering are better stated by the dictum "A qualitative model is power!"

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Timothy F. Thompson is a senior engineer at the Westinghouse R&D Center. He has developed several knowledge-based systems, ranging from diagnosis of large electromechanical systems to the configuration of power distribution systems.

Thompson received his BSEE from the University of Pittsburgh and his MSEE from Carnegie-Mellon University. He is a member of the IEEE, ACM, AAAI, and ACL.

He can be contacted at the Westinghouse R&D Center, 1310 Beulah Rd., Pittsburgh, PA 15235.

William J. Clancey is a senior research associate in computer science at Stanford University's Knowledge Systems Laboratory. He has been active in expert system research since he joined the Mycin project in 1975.

Clancey received his BA in mathematical sciences from Rice University and his PhD in computer science from Stanford University. Clancey is a cofounder of Teknowledge, Inc., and an associate editor of *IEEE Pattern Analysis and Machine Intelligence.*

He can be reached at the Stanford Knowledge Systems Laboratory, 701 Welch Road, Building C, Palo Alto, CA 94304.

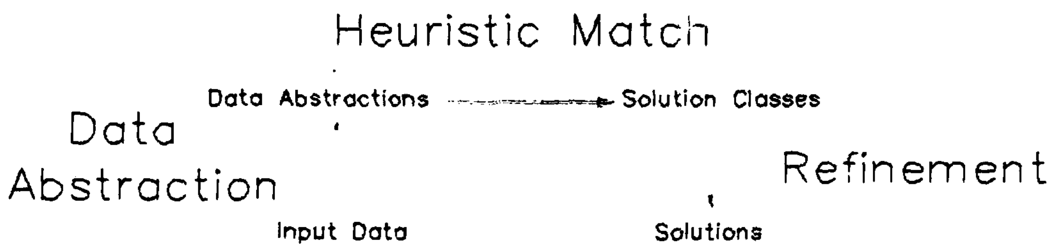

Figure 1: Heuristic Classification

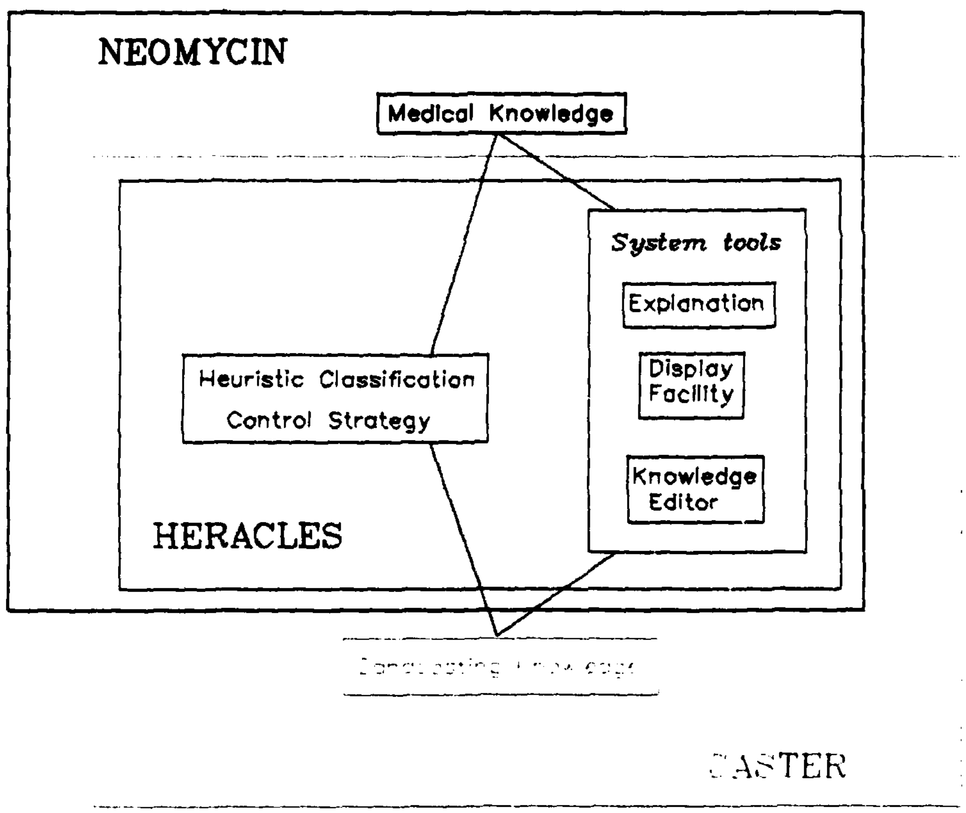

Figure 2: The Heracles Environment and the Neomycin and Caster applications

```
(META-RULE022
        PREMISE (SET-WITH-NEW (UNCLARIFIED-FINDING NEW.DATA)
                 FOCUSDATUM)
        ACTION (TASK CLARIFY-FINDING FOCUSDATUM)
        TASK FORWARD-REASON)
```

Figure 3: A sample metarule.

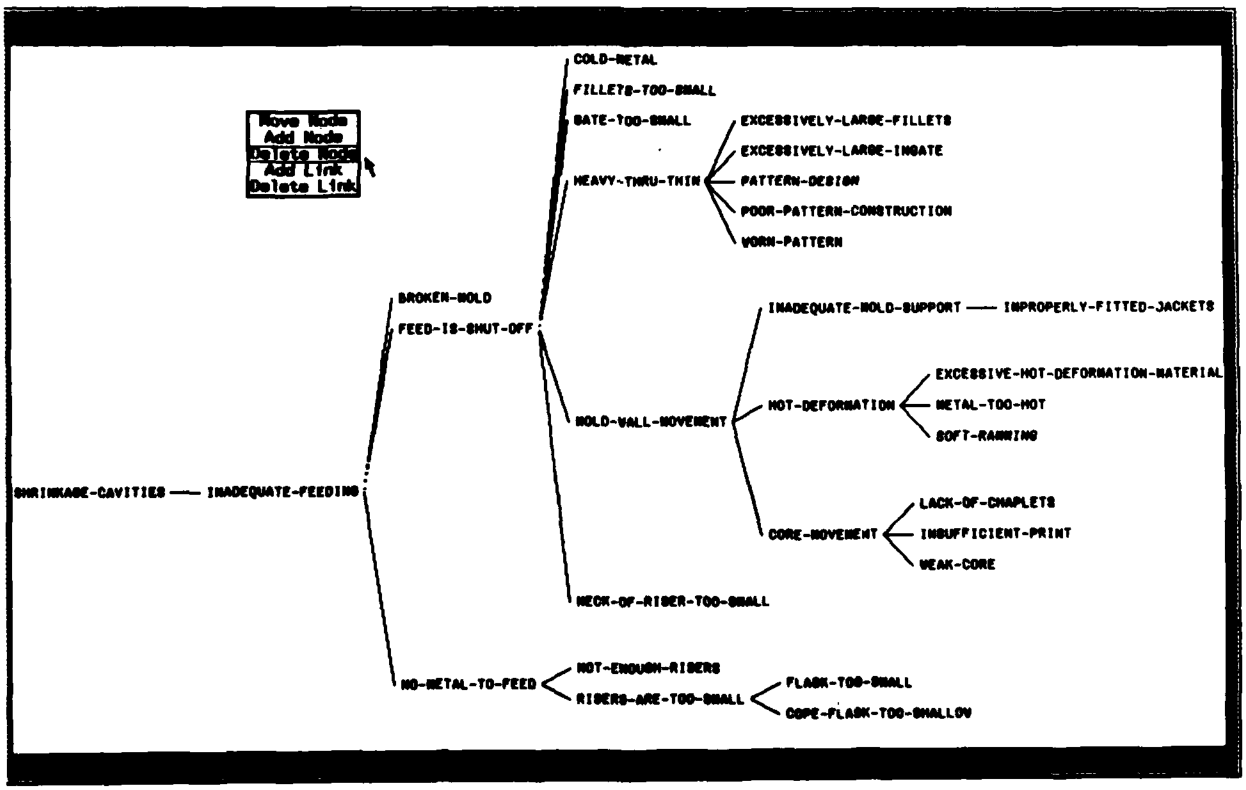

Figure 4: Using the knowledge editor.

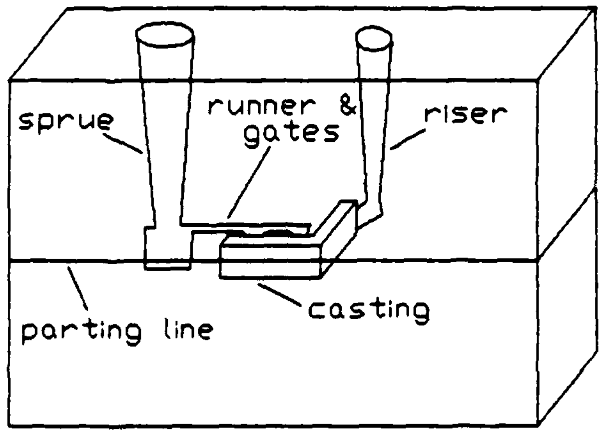

Figure 5: Illustration of sandcasting

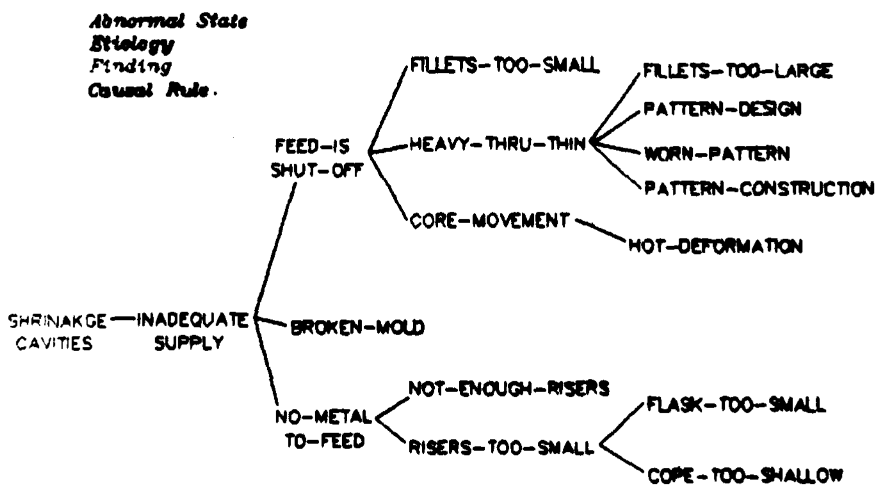

Figure 6: Causal network for shrinkage cavities.
[Shrinkage-cavities is a finding; ultimate etiologies are terminal nodes on the right; abnormal states appear as intermediate nodes linked by causal rules.]

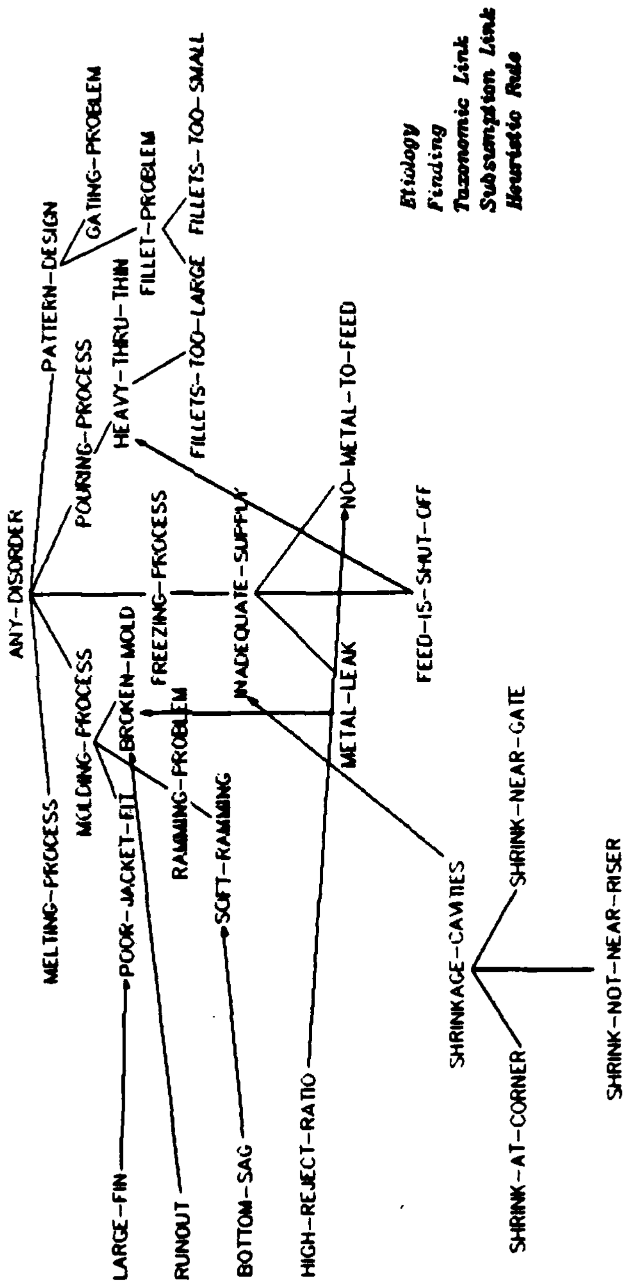

Figure 7: Knowledge of shrinkage cavities organized for heuristic classification.
[Etiologies appear below ANY-DISORDER; findings on left are linked to their causes by heuristic rules and to each other by subsumption.]

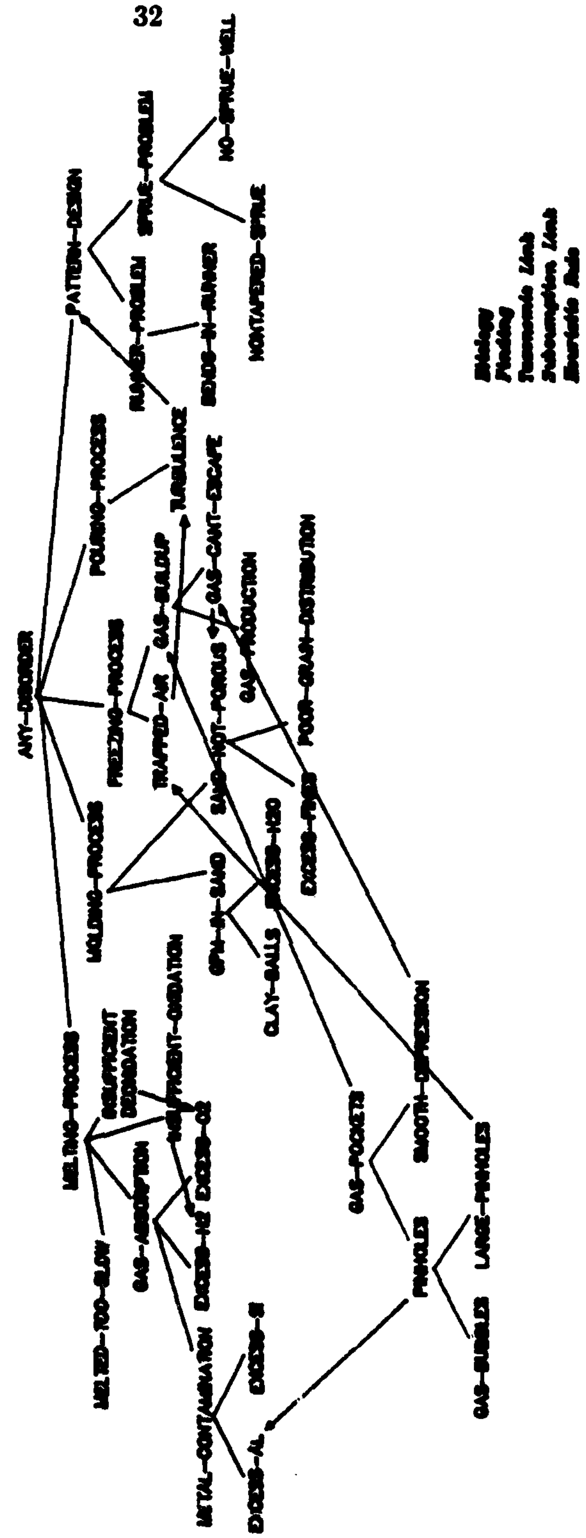

Figure 8: Partial qualitative model for gas defects.
[Etiologies appear below ANY-DISORDER; findings below are linked by subsumption; arrow lines indicate heuristic rules.]

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List of Figures

Personnel Analysis Division,
AF/MPXA
5C360, The Pentagon
Washington, DC 20330

Air Force Human Resources Lab
AFHRL/MPD
Brooks AFB, TX 78235

AFOSR,
Life Sciences Directorate
Bolling Air Force Base
Washington, DC 20332

Dr. Robert Ahlers
Code N711
Human Factors Laboratory
Naval Training Systems Center
Orlando, FL 32813

Dr. Ed Aiken
Navy Personnel R&D Center
San Diego, CA 92152-6800

Dr. William E. Alley
AFHRL/MOT
Brooks AFB, TX 78235

Dr. Earl A. Alluisi
HQ, AFHRL (AFSC)
Brooks AFB, TX 78235

Dr. John R. Anderson
Department of Psychology
Carnegie-Mellon University
Pittsburgh, PA 15213

Dr. Nancy S. Anderson
Department of Psychology
University of Maryland
College Park, MD 20742

Dr. Steve Andriole
George Mason University
School of Information
Technology & Engineering
4400 University Drive
Fairfax, VA 22030

Dr. John Annett
University of Warwick
Department of Psychology
Coventry CV4 7AJ
ENGLAND

Dr. Phipps Arabie
University of Illinois
Department of Psychology
603 E. Daniel St.
Champaign, IL 61820

Technical Director, ARI
5001 Eisenhower Avenue
Alexandria, VA 22333

Special Assistant for Projec
OASN(M&RA)
5D800, The Pentagon
Washington, DC 20350

Dr. Michael Atwood
ITT - Programming
1000 Oronoque Lane
Stratford, CT 06497

Dr. Patricia Baggett
University of Colorado
Department of Psychology
Box 345
Boulder, CO 80309

Dr. Eva L. Baker
UCLA Center for the Study
of Evaluation
145 Moore Hall
University of California
Los Angeles, CA 90024

Dr. James D. Baker
Director of Automation
Allen Corporation of America
401 Wythe Street
Alexandria, VA 22314

Dr. Meryl S. Baker
Navy Personnel R&D Center
San Diego, CA 92152-6800

Dr. Donald E. Bamber
Code 71
Navy Personnel R & D Center
San Diego, CA 92152-6800

Mr. J. Barber
HQS, Department of the Army
DAPE-ZBR
Washington, DC 20310

Capt. J. Jean Belanger
Training Development Division
Canadian Forces Training System
CFTSHQ, CFB Trenton
Astra, Ontario, KOK
CANADA

CDR Robert J. Biersner, USN
Naval Biodynamics Laboratory
P. O. Box 29407
New Orleans, LA 70189

Dr. Menucha Birenbaum
School of Education
Tel Aviv University
Tel Aviv, Ramat Aviv 69978
ISRAEL

Dr. Werner P. Birke
Personalstammamt der Bundeswehr
Kolner Strasse 262
D-5000 Koeln 90
FEDERAL REPUBLIC OF GERMANY

Dr. Gautam Biswas
Department of Computer Science
University of South Carolina
Columbia, SC 29208

Dr. John Black
College, Columbia Univ.
525 West 121st Street
New York, NY 10027

Dr. Arthur S. Blaiwes
Code N711
Naval Training Systems Center
Orlando, FL 32813

Dr. Robert Blanchard
Navy Personnel R&D Center
San Diego, CA 92152-6800

Dr. Jeff Bonar
Learning R&D Center
University of Pittsburgh
Pittsburgh, PA 15260

Dr. J. C. Boudreaux
Center for Manufacturing
Engineering
National Bureau of Standards
Gaithersburg, MD 20899

Dr. Gordon H. Bower
Department of Psychology
Stanford University
Stanford, CA 94306

Dr. Richard Braby
NTSC Code 10
Orlando, FL 32751

Dr. Robert Breaux
Code N-095R
Naval Training Systems Cente
Orlando, FL 32813

Dr. John S. Brown
XEROX Palo Alto Research
Center
3333 Coyote Road
Palo Alto, CA 94304

Dr. Bruce Buchanan
Computer Science Department
Stanford University
Stanford, CA 94305

Dr. Howard Burrows
National Institute of Health
Bldg. 10, Room 5C-106
Bethesda, MD 20892

Dr. Patricia A. Butler
OERI
555 New Jersey Ave., NW
Washington, DC 20208

Dr. Tom Cafferty
Dept. of Psychology
University of South Carolina
Columbia, SC 29208

Dr. Robert Calfee
School of Education
Stanford University
Stanford, CA 94305

Joanne Capper
Center for Research into Practice
1718 Connecticut Ave., N.W.
Washington, DC 20009

Dr. Jaime Carbonell
Carnegie-Mellon University
Department of Psychology
Pittsburgh, PA 15213

Mr. James W. Carey
Commandant (G-PTE)
U.S. Coast Guard
2100 Second Street, S.W.
Washington, DC 20593

Dr. Susan Carey
Harvard Graduate School of
Education
337 Gutman Library
Appian Way
Cambridge, MA 02138

Dr. Pat Carpenter
Carnegie-Mellon University
Department of Psychology
Pittsburgh, PA 15213

Prof. John W. Carr III
Department of Computer Science
Moore School of
Electrical Engineering
University of Pennsylvania
Philadelphia, PA 19104

Dr. Robert Carroll
OP 01B7
Washington, DC 20370

LCDR Robert Carter
Office of the Chief
of Naval Operations
OP-01B
Pentagon
Washington, DC 20350-2000

Dr. Fred Chang
Navy Personnel R&D Center
Code 51
San Diego, CA 92152-6800

Dr. Alphonse Chapanis
8415 Bellona Lane
Suite 210
Buxton Towers
Baltimore, MD 21204

Dr. Davida Charney
Department of Psychology
Carnegie-Mellon University
Schenley Park
Pittsburgh, PA 15213

Dr. Eugene Charniak
Brown University
Computer Science Department
Providence, RI 02912

Dr. Paul R. Chatelier
OUSDRE
Pentagon
Washington, DC 20350-2000

Dr. Michelene Chi
Learning R & D Center
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15213

Mr. Raymond E. Christal
AFHRL/MOE
Brooks AFB, TX 78235

Dr. Yee-Yeen Chu
Perceptronics, Inc.
21111 Erwin Street
Woodland Hills, CA 91367-371

Dr. William Clancey
Stanford University
Knowledge Systems Laboratory
701 Welch Road, Bldg. C
Palo Alto, CA 94304

Chief of Naval Education
and Training
Liaison Office
Air Force Human Resource Lab
Operations Training Division
Williams AFB, AZ 85224

Assistant Chief of Staff
for Research, Development,
Test, and Evaluation
Naval Education and
Training Command (N-5)
NAS Pensacola, FL 32508

Dr. Allan M. Collins
Bolt Beranek & Newman, Inc.
50 Moulton Street
Cambridge, MA 02138

Dr. John J. Collins
Director, Field Research
Office, Orlando
NPRDC Liaison Officer
NTSC Orlando, FL 32813

Dr. Stanley Collyer
Office of Naval Technology
Code 222
800 N. Quincy Street
Arlington, VA 22217-5000

Dr. Lynn A. Cooper
Learning R&D Center
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15213

Dr. Meredith P. Crawford
American Psychological Association
Office of Educational Affairs
1200 17th Street, N.W.
Washington, DC 20036

Dr. Hans Crombag
University of Leyden
Education Research Center
Boerhaavelaan 2
2334 EN Leyden
The NETHERLANDS

LT Judy Crookshanks
Chief of Naval Operations
OP-112G5
Washington, DC 20370-2000

Dr. Kenneth B. Cross
Anacapa Sciences, Inc.
P.O. Drawer Q
Santa Barbara, CA 93102

Dr. Mary Cross
Department of Education
Adult Literacy Initiative
Room 4145
400 Maryland Avenue, SW
Washington, DC 20202

CTB/McGraw-Hill Library
2500 Garden Road
Monterey, CA 93940

CAPT P. Michael Curran
Office of Naval Research
800 N. Quincy St.
Code 125
Arlington, VA 22217-5000

Dr. Cary Czichon
Intelligent Instructional Sy
Texas Instruments AI Lab
P.O. Box 660245
Dallas, TX 75266

Bryan Dallman
AFHRL/LRT
Lowry AFB, CO 80230

LT John Deaton
ONR Code 125
800 N. Quincy Street
Arlington, VA 22217-5000

Dr. Natalie Dehn
Department of Computer and
Information Science
University of Oregon
Eugene, OR 97403

Dr. Gerald F. DeJong
Artificial Intelligence Grou
Coordinated Science Laborato
University of Illinois
Urbana, IL 61801

Goery Delacote
Directeur de L'informatique
Scientifique et Technique
CNRS
15, Quai Anatole France
75700 Paris FRANCE

Mr. Robert Denton
AFMPC/MPCYPR
Randolph AFB, TX 78150

Mr. Paul DiRenzo
Commandant of the Marine Corps
Code LBC-4
Washington, DC 20380

Dr. R. K. Dismukes
Associate Director for Life Sciences
AFOSR
Bolling AFB
Washington, DC 20332

Defense Technical
Information Center
Cameron Station, Bldg 5
Alexandria, VA 22314
Attn: TC
(12 Copies)

Dr. Thomas M. Duffy
Communications Design Center
Carnegie-Mellon University
Schenley Park
Pittsburgh, PA 15213

Barbara Eason
Military Educator's
Resource Network
InterAmerica Research Associates
1555 Wilson Blvd
Arlington, VA 22209

Edward E. Eddowes
CNATRA N301
Naval Air Station
Corpus Christi, TX 78419

Dr. John Ellis
Navy Personnel R&D Center
San Diego, CA 92252

Dr. Richard Elster
Deputy Assistant Secretary
of the Navy (Manpower)
OASN (M&RA)
Department of the Navy
Washington, DC 20350-1000

Dr. Susan Embretson
University of Kansas
Psychology Department
426 Fraser
Lawrence, KS 66045

Dr. Randy Engle
Department of Psychology
University of South Carolina
Columbia, SC 29208

Lt. Col. Rich Entlich
HQ, Department of the Army
OCSA(DACS-DPM)
Washington, DC 20310

Dr. Susan Epstein
Hunter College
144 S. Mountain Avenue
Montclair, NJ 07042

Dr. William Epstein
University of Wisconsin
W. J. Brogden Psychology Bld
1202 W. Johnson Street
Madison, WI 53706

ERIC Facility-Acquisitions
4833 Rugby Avenue
Bethesda, MD 20014

Dr. K. Anders Ericsson
University of Colorado
Department of Psychology
Boulder, CO 80309

Dr. Edward Esty
Department of Education, OER
Room 717D
1200 19th St., NW
Washington, DC 20208

Dr. Beatrice J. Farr
Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

Dr. Marshall J. Farr
2520 North Vernon Street
Arlington, VA 22207

Dr. Pat Federico
Code 511
NPRDC
San Diego, CA 92152-6800

Dr. Jerome A. Feldman
University of Rochester
Computer Science Department
Rochester, NY 14627

Dr. Paul Feltovich
Southern Illinois University
School of Medicine
Medical Education Department
P.O. Box 3926
Springfield, IL 62708

Mr. Wallace Feurzeig
Educational Technology
Bolt Beranek & Newman
10 Moulton St.
Cambridge, MA 02238

Dr. Craig I. Fields
ARPA
1400 Wilson Blvd.
Arlington, VA 22209

Dr. Gerhard Fischer
University of Colorado
Department of Computer Science
Boulder, CO 80309

J. D. Fletcher
9931 Corsica Street
Vienna VA 22180

Dr. Linda Flower
Carnegie-Mellon University
Department of English
Pittsburgh, PA 15213

Dr. Kenneth D. Forbus
University of Illinois
Department of Computer Science
1304 West Springfield Avenue
Urbana, IL 61801

Dr. Barbara A. Fox
University of Colorado
Department of Linguistics
Boulder, CO 80309

Dr. Carl H. Frederiksen
McGill University
3700 McTavish Street
Montreal, Quebec H3A 1Y2
CANADA

Dr. John R. Frederiksen
Bolt Beranek & Newman
50 Moulton Street
Cambridge, MA 02138

Dr. Norman Frederiksen
Educational Testing Service
Princeton, NJ 08541

Dr. Alfred R. Fregly
AFOSR/NL
Bolling AFB, DC 20332

Dr. Bob Frey
Commandant (G-P-1/2)
USCG HQ
Washington, DC 20593

Dr. Alinda Friedman
Department of Psychology
University of Alberta
Edmonton, Alberta
CANADA T6G 2E9

Julie A. Gadsden
Information Technology
Applications Division
Admiralty Research Establish
Portsdown, Portsmouth PO6 4A
UNITED KINGDOM

Dr. R. Edward Geiselman
Department of Psychology
University of California
Los Angeles, CA 90024

Dr. Michael Genesereth
Stanford University
Computer Science Department
Stanford, CA 94305

Dr. Dedre Gentner
University of Illinois
Department of Psychology
603 E. Daniel St.
Champaign, IL 61820

Dr. Robert Glaser
Learning Research
& Development Center
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15260

Dr. Arthur M. Glenberg
University of Wisconsin
W. J. Brogden Psychology Bldg
1202 W. Johnson Street
Madison, WI 53706

Dr. Marvin D. Glock
13 Stone Hall
Cornell University
Ithaca, NY 14853

Dr. Gene L. Gloye
Office of Naval Research
Detachment
1030 E. Green Street
Pasadena, CA 91106-2485

Dr. Sam Glucksberg
Department of Psychology
Princeton University
Princeton, NJ 08540

Dr. Joseph Goguen
Computer Science Laboratory
SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025

Dr. Sherrie Gott
AFHRL/MODJ
Brooks AFB, TX 78235

Jordan Grafman, Ph.D.
2021 Lyttonsville Road
Silver Spring, MD 20910

Dr. Richard H. Granger
Department of Computer Science
University of California, Irvine
Irvine, CA 92717

Dr. Wayne Gray
Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

Dr. James G. Greeno
University of California
Berkeley, CA 94720

H. William Greenup
Education Advisor (E031)
Education Center, MCDEC
Quantico, VA 22134

Dipl. Pad. Michael W. Habon
Universitat Dusseldorf
Erziehungswissenschaftliches
Universitatsstr. 1
D-4000 Dusseldorf 1
WEST GERMANY

Prof. Edward Haertel
School of Education
Stanford University
Stanford, CA 94305

Dr. Henry M. Halff
Halff Resources, Inc.
4918 33rd Road, North
Arlington, VA 22207

Dr. Ronald K. Hambleton
Prof. of Education & Psychol
University of Massachusetts
at Amherst
Hills House
Amherst, MA 01003

Dr. Cheryl Hamel
NTSC
Orlando, FL 32813

Dr. Bruce W. Hamill
Johns Hopkins University
Applied Physics Laboratory
Johns Hopkins Road
Laurel, MD 20707

Dr. Ray Hannapel
Scientific and Engineering
Personnel and Education
National Science Foundation
Washington, DC 20550

Stevan Harnad
Editor, The Behavioral and
Brain Sciences
20 Nassau Street, Suite 240
Princeton, NJ 08540

Mr. William Hartung
PEAM Product Manager
Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

Dr. Wayne Harvey
SRI International
333 Ravenswood Ave.
Room B-S324
Menlo Park, CA 94025

Dr. Reid Hastie
Northwestern University
Department of Psychology
Evanston, IL 60201

Prof. John R. Hayes
Carnegie-Mellon University
Department of Psychology
Schenley Park
Pittsburgh, PA 15213

Dr. Barbara Hayes-Roth
Department of Computer Science
Stanford University
Stanford, CA 95305

Dr. Frederick Hayes-Roth
Teknowledge
525 University Ave.
Palo Alto, CA 94301

Dr. Joan I. Heller
505 Haddon Road
Oakland, CA 94606

Dr. James Hendler
Dept. of Computer Science
University of Maryland
College Park, MD 20742

Dr. Jim Hollan
Intelligent Systems Group
Institute for
Cognitive Science (C-015)
UCSD
La Jolla, CA 92093

Dr. Melissa Holland
Army Research Institute for
Behavioral and Social Sci
5001 Eisenhower Avenue
Alexandria, VA 22333

Dr. Robert W. Holt
Department of Psychology
George Mason University
4400 University Drive
Fairfax, VA 22030

Dr. Keith Holyoak
University of Michigan
Human Performance Center
330 Packard Road
Ann Arbor, MI 48109

Prof. Lutz F. Hornke
Institut fur Psychologie
RWTH Aachen
Jaegerstrasse 17/19
D-5100 Aachen
WEST GERMANY

Mr. Dick Hoshaw
OP-135
Arlington Annex
Room 2834
Washington, DC 20350

Dr. James Howard
Dept. of Psychology
Human Performance Laboratory
Catholic University of
America
Washington, DC 20064

Dr. Steven Hunka
Department of Education
University of Alberta
Edmonton, Alberta
CANADA

Dr. Earl Hunt
Department of Psychology
University of Washington
Seattle, WA 98105

Dr. Ed Hutchins
Intelligent Systems Group
Institute for
Cognitive Science (C-015)
UCSD
La Jolla, CA 92093

Dr. Dillon Inouye
WICAT Education Institute
Provo, UT 84057

Dr. Alice Isen
Department of Psychology
University of Maryland
Catonsville, MD 21228

Dr. Zachary Jacobson
Bureau of Management Consulting
365 Laurier Avenue West
Ottawa, Ontario K1A 0S5
CANADA

Dr. Robert Jannarone
Department of Psychology
University of South Carolina
Columbia, SC 29208

Dr. Claude Janvier
Directeur, CIRADE
Universite' du Quebec a Montreal
Montreal, Quebec H3C 3P8
CANADA

COL Dennis W. Jarvi
Commander
AFHRL
Brooks AFB, TX 78235-5601

Dr. Robin Jeffries
Hewlett-Packard Laboratories
P.O. Box 10490
Palo Alto, CA 94303-0971

Dr. Robert Jernigan
Decision Resource Systems
5595 Vantage Point Road
Columbia, MD 21044

Margaret Jerome
c/o Dr. Peter Chandler
83, The Drive
Hove
Sussex
UNITED KINGDOM

Dr. Joseph E. Johnson
Assistant Dean for
Graduate Studies
College of Science and Mathe
University of South Carolina
Columbia, SC 29208

Dr. Richard Johnson
Boise State University
Simplot/Micron
Technology Center
Boise, ID 83725

CDR Tom Jones
ONR Code 125
800 N. Quincy Street
Arlington, VA 22217-5000

Dr. Douglas A. Jones
P.O. Box 6640
Lawrenceville
NJ 08648

Col. Dominique Jouslin de No
Etat-Major de l'Armee de Ter
Centre de Relations Humaines
3 Avenue Octave Greard
75007 Paris
FRANCE

Dr. Marcel Just
Carnegie-Mellon University
Department of Psychology
Schenley Park
Pittsburgh, PA 15213

Dr. Milton S. Katz
Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

Dr. Scott Kelso
Haskins Laboratories,
270 Crown Street
New Haven, CT 06510

Dr. Dennis Kibler
University of California
Department of Information
and Computer Science
Irvine, CA 92717

Dr. David Kieras
University of Michigan
Technical Communication
College of Engineering
1223 E. Engineering Building
Ann Arbor, MI 48109

Dr. Peter Kincaid
Training Analysis
& Evaluation Group
Department of the Navy
Orlando, FL 32813

Dr. Walter Kintsch
Department of Psychology
University of Colorado
Campus Box 345
Boulder, CO 80302

Dr. Paula Kirk
Oakridge Associated Universities
University Programs Division
P.O. Box 117
Oakridge, TN 37831-0117

Dr. David Klahr
Carnegie-Mellon University
Department of Psychology
Schenley Park
Pittsburgh, PA 15213

Dr. Mazie Knerr
Program Manager
Training Research Division
HumRRO
1100 S. Washington
Alexandria, VA 22314

Dr. Janet L. Kolodner
Georgia Institute of Technology
School of Information
& Computer Science
Atlanta, GA 30332

Dr. Stephen Kosslyn
Harvard University
1236 William James Hall
33 Kirkland St.
Cambridge, MA 02138

Dr. Kenneth Kotovsky
Department of Psychology
Community College of
Allegheny County
800 Allegheny Avenue
Pittsburgh, PA 15233

Dr. David H. Krantz
2 Washington Square Village
Apt. # 15J
New York, NY 10012

Dr. Benjamin Kuipers
University of Texas at Austi
Department of Computer Scien
T.S. Painter Hall 3.28
Austin, Texas 78712

Dr. David R. Lambert
Naval Ocean Systems Center
Code 441T
271 Catalina Boulevard
San Diego, CA 92152-6800

Dr. Pat Langley
University of California
Department of Information
and Computer Science
Irvine, CA 92717

M. Diane Langston
Communications Design Center
Carnegie-Mellon University
Schenley Park
Pittsburgh, PA 15213

Dr. Jill Larkin
Carnegie-Mellon University
Department of Psychology
Pittsburgh, PA 15213

Dr. Robert Lawler
Information Sciences, FRL
GTE Laboratories, Inc.
40 Sylvan Road
Waltham, MA 02254

Dr. Paul E. Lehner
PAR Technology Corp.
7926 Jones Branch Drive
Suite 170
McLean, VA 22102

Dr. Alan M. Lesgold
Learning R&D Center
University of Pittsburgh
Pittsburgh, PA 15260

Dr. Alan Leshner
Deputy Division Director
Behavioral and Neural Sciences
National Science Foundation
1800 G Street
Washington, DC 20550

Dr. Jim Levin
University of California
Laboratory for Comparative
Human Cognition
D003A
La Jolla, CA 92093

Dr. John Levine
Learning R&D Center
University of Pittsburgh
Pittsburgh, PA 15260

Dr. Michael Levine
Educational Psychology
210 Education Bldg.
University of Illinois
Champaign, IL 61801

Dr. Charles Lewis
Faculteit Sociale Wetenschappen
Rijksuniversiteit Groningen
Oude Boteringestraat 23
9712GC Groningen
The NETHERLANDS

Dr. Clayton Lewis
University of Colorado
Department of Computer Science
Campus Box 430
Boulder, CO 80309

Library
Naval War College
Newport, RI 02940

Library
Naval Training Systems Cente
Orlando, FL 32813

Dr. Charlotte Linde
SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025

Dr. Marcia C. Linn
Lawrence Hall of Science
University of California
Berkeley, CA 94720

Dr. Robert Linn
College of Education
University of Illinois
Urbana, IL 61801

Dr. Don Lyon
P. O. Box 44
Higley, AZ 85236

Dr. Jane Malin
Mail Code SR 111
NASA Johnson Space Center
Houston, TX 77058

Dr. William L. Maloy
Chief of Naval Education
and Training
Naval Air Station
Pensacola, FL 32508

Dr. Sandra P. Marshall
Dept. of Psychology
San Diego State University
San Diego, CA 92182

Dr. Manton M. Matthews
Department of Computer Scien
University of South Carolina
Columbia, SC 29208

Dr. Richard E. Mayer
Department of Psychology
University of California
Santa Barbara, CA 93106

Dr. James McBride
Psychological Corporation
c/o Harcourt, Brace,
Javanovich Inc.
1250 West 6th Street
San Diego, CA 92101

Dr. David J. McGuinness
Gallaudet College
800 Florida Avenue, N.E.
Washington, DC 20002

Dr. Kathleen McKeown
Columbia University
Department of Computer Science
New York, NY 10027

Dr. Joe McLachlan
Navy Personnel R&D Center
San Diego, CA 92152-6800

Dr. James McMichael
Assistant for MPT Research,
Development, and Studies
OP 01B7
Washington, DC 20370

Dr. Barbara Means
Human Resources
Research Organization
1100 South Washington
Alexandria, VA 22314

Dr. Douglas L. Medin
Department of Psychology
University of Illinois
603 E. Daniel Street
Champaign, IL 61820

Dr. Arthur Melmed
U. S. Department of Education
724 Brown
Washington, DC 20208

Dr. Jose Mestre
Department of Physics
Hasbrouck Laboratory
University of Massachusetts
Amherst, MA 01003

Dr. Al Meyrowitz
Office of Naval Research
Code 1133
800 N. Quincy
Arlington, VA 22217-5000

Dr. Ryszard S. Michalski
University of Illinois
Department of Computer Scien
1304 West Springfield Avenue
Urbana, IL 61801

Prof. D. Michie
The Turing Institute
36 North Hanover Street
Glasgow G1 2AD, Scotland
UNITED KINGDOM

Dr. George A. Miller
Department of Psychology
Green Hall
Princeton University
Princeton, NJ 08540

Dr. James R. Miller
MCC
9430 Research Blvd.
Echelon Building #1, Suite 2
Austin, TX 78759

Dr. Mark Miller
Computer*Thought Corporation
1721 West Plano Parkway
Plano, TX 75075

Dr. Andrew R. Molnar
Scientific and Engineering
Personnel and Education
National Science Foundation
Washington, DC 20550

Dr. William Montague
NPRDC Code 13
San Diego, CA 92152-6800

Dr. Tom Moran
Xerox PARC
3333 Coyote Hill Road
Palo Alto, CA 94304

Dr. Melvyn Moy
Navy Personnel R & D Center
San Diego, CA 92152-6800

Dr. Allen Munro
Behavioral Technology
Laboratories - USC
1845 S. Elena Ave., 4th Floor
Redondo Beach, CA 90277

Director,
Decision Support
Systems Division, NMPC
Naval Military Personnel Command
N-164
Washington, DC 20370

Director,
Distribution Department, NMPC
N-4
Washington, DC 20370

Director,
Overseas Duty Support
Program, NMPC
N-62
Washington, DC 20370

Head, HRM Operations Branch,
NMPC
N-62F
Washington, DC 20370

Assistant for Evaluation,
Analysis, and MIS, NMPC
N-6C
Washington, DC 20370

Spec. Asst. for Research, Experimental & Academic Programs,
NTTC (Code 016)
NAS Memphis (75)
Millington, TN 38054

Director,
Research & Analysis Div.,
NAVCRUITCOM Code 22
4015 Wilson Blvd.
Arlington, VA 22203

Technical Director
Navy Health Research Center
P.O. Box 85122
San Diego, CA 92138

Leadership Management Educat
and Training Project Offi
Naval Medical Command
Code 05C
Washington, DC 20372

Technical Director,
Navy Health Research Ctr.
P.O. Box 85122
San Diego, CA 92138

Dr. T. Niblett
The Turing Institute
36 North Hanover Street
Glasgow G1 2AD, Scotland
UNITED KINGDOM

Dr. Richard E. Nisbett
University of Michigan
Institute for Social Researc
Room 5261
Ann Arbor, MI 48109

Dr. Mary Jo Nissen
University of Minnesota
N218 Elliott Hall
Minneapolis, MN 55455

Dr. Donald A. Norman
Institute for Cognitive Scie
University of California
La Jolla, CA 92093

Director, Training Laborator
NPRDC (Code 05)
San Diego, CA 92152-6800

Director, Manpower and Perso
Laboratory,
NPRDC (Code 06)
San Diego, CA 92152-6800

Director, Human Factors
& Organizational Systems
NPRDC (Code 07)
San Diego, CA 92152-6800

Fleet Support Office,
NPRDC (Code 301)
San Diego, CA 92152-6800

Library, NPRDC
Code P201L
San Diego, CA 92152-6800

Commanding Officer,
Naval Research Laboratory
Code 2627
Washington, DC 20390

Dr. Harold F. O'Neil, Jr.
School of Education - WPH 801
Department of Educational
Psychology & Technology
University of Southern California
Los Angeles, CA 90089-0031

Dr. Stellan Ohlsson
Learning R & D Center
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15213

Director, Research Programs,
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5000

Office of Naval Research,
Code 1133
800 N. Quincy Street
Arlington, VA 22217-5000

Office of Naval Research,
Code 1142
800 N. Quincy St.
Arlington, VA 22217-5000

Office of Naval Research,
Code 1142EP
800 N. Quincy Street
Arlington, VA 22217-5000

Office of Naval Research,
Code 1142PT
800 N. Quincy Street
Arlington, VA 22217-5000
(6 Copies)

Director, Technology Programs,
Office of Naval Research
Code 12
800 North Quincy Street
Arlington, VA 22217-5000

Special Assistant for Marine
Corps Matters,
ONR Code 00MC
800 N. Quincy St.
Arlington, VA 22217-5000

Assistant for Long Range
Requirements,
CNO Executive Panel
OP 00K
2000 North Beauregard Street
Alexandria, VA 22311

Assistant for MPT Research,
Development and Studies
OP 01B7
Washington, DC 20370

Dr. Judith Orasanu
Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

Dr. Jesse Orlansky
Institute for Defense Analys
1801 N. Beauregard St.
Alexandria, VA 22311

Prof. Seymour Papert
20C-109
Massachusetts Institute
of Technology
Cambridge, MA 02139

CDR R. T. Parlette
Chief of Naval Operations
OP-112G
Washington, DC 20370-2000

Dr. James Paulson
Department of Psychology
Portland State University
P.O. Box 751
Portland, OR 97207

Dr. Douglas Pearse
DCIEM
Box 2000
Downsview, Ontario
CANADA

Dr. Virginia E. Pendergrass
Code 711
Naval Training Systems Center
Orlando, FL 32813-7100

Dr. Robert Penn
NPRDC
San Diego, CA 92152-6800

Dr. Nancy Pennington
University of Chicago
Graduate School of Business
1101 E. 58th St.
Chicago, IL 60637

Military Assistant for Training and
Personnel Technology,
OUSD (R & E)
Room 3D129, The Pentagon
Washington, DC 20301-3080

Dr. Ray Perez
ARI (PERI-II)
5001 Eisenhower Avenue
Alexandria, VA 2233

Dr. David N. Perkins
Educational Technology Center
337 Gutman Library
Appian Way
Cambridge, MA 02138

LCDR Frank C. Petho, MSC, USN
CNATRA Code N36, Bldg. 1
NAS
Corpus Christi, TX 78419

Administrative Sciences Department,
Naval Postgraduate School
Monterey, CA 93940

Department of Computer Science,
Naval Postgraduate School
Monterey, CA 93940

Department of Operations Research,
Naval Postgraduate School
Monterey, CA 93940

Dr. Tjeerd Plomp
Twente University of Technol
Department of Education
P.O. Box 217
7500 AE ENSCHEDE

THE NETHERLANDS

Dr. Martha Polson
Department of Psychology
Campus Box 346
University of Colorado
Boulder, CO 80309

Dr. Peter Polson
University of Colorado
Department of Psychology
Boulder, CO 80309

Dr. Steven E. Poltrock
MCC
9430 Research Blvd.
Echelon Bldg #1
Austin, TX 78759-6509

Dr. Harry E. Pople
University of Pittsburgh
Decision Systems Laboratory
1360 Scaife Hall
Pittsburgh, PA 15261

Dr. Mary C. Potter
Department of Psychology
MIT (E-10-032)
Cambridge, MA 02139

Dr. Joseph Psotka
ATTN: PERI-1C
Army Research Institute
5001 Eisenhower Ave.
Alexandria, VA 22333

Dr. Roy Rada
National Library of Medicine
Bethesda, MD 20894

Dr. Lynne Reder
Department of Psychology
Carnegie-Mellon University
Schenley Park
Pittsburgh, PA 15213

Brian Reiser
Department of Psychology
Princeton University
Princeton, NJ 08544

Dr. James A. Reggia
University of Maryland
School of Medicine
Department of Neurology
22 South Greene Street
Baltimore, MD 21201

CDR Karen Reider
Naval School of Health Sciences
National Naval Medical Center
Bldg. 141
Washington, DC 20814

Dr. Fred Reif
Physics Department
University of California
Berkeley, CA 94720

Dr. Lauren Resnick
Learning R & D Center
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15213

Dr. Mary S. Riley
Program in Cognitive Science
Center for Human Information
Processing
University of California
La Jolla, CA 92093

William Rizzo
Code 712
Naval Training Systems Center
Orlando, FL 32813

Dr. Linda G. Roberts
Science, Education, and
Transportation Program
Office of Technology Assessment
Congress of the United States
Washington, DC 20510

Dr. Andrew M. Rose
American Institutes
for Research
1055 Thomas Jefferson St., NW
Washington, DC 20007

Dr. William B. Rouse
Search Technology, Inc.
25-b Technology Park/Atlanta
Norcross, GA 30092

Dr. Donald Rubin
Statistics Department
Science Center, Room 608
1 Oxford Street
Harvard University
Cambridge, MA 02138

Dr. David Rumelhart
Center for Human
Information Processing
Univ. of California
La Jolla, CA 92093

Ms. Riitta Ruotsalainen
General Headquarters
Training Section
Military Psychology Office
PL 919
SF-00101 Helsinki 10, FINLAN

Dr. Michael J. Samet
Perceptronics, Inc
6271 Variel Avenue
Woodland Hills, CA 91364

Dr. Roger Schank
Yale University
Computer Science Department
P.O. Box 2158
New Haven, CT 06520

Dr. W. L. Scherlis
Dept. of Computer Science
Carnegie-Mellon University
Schenley Park
Pittsburgh, PA 15213

Mrs. Birgitte Schneidelbach
Forsvarets Center for Leders
Christianshavns Voldgade 8
1424 Kobenhavn K
DENMARK

Dr. Walter Schneider
Learning R&D Center
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15260

Dr. Alan H. Schoenfeld
University of California
Department of Education
Berkeley, CA 94720

Dr. Janet Schofield
Learning R&D Center
University of Pittsburgh
Pittsburgh, PA 15260

Dr. Marc Sebrechts
Department of Psychology
Wesleyan University
Middletown, CT 06475

Dr. Judith Segal
OERI
555 New Jersey Ave., NW
Washington, DC 20208

Dr. Robert J. Seidel
US Army Research Institute
5001 Eisenhower Ave.
Alexandria, VA 22333

Dr. Ramsay W. Selden
Assessment Center
CCSSO
Suite 379
400 N. Capitol, NW
Washington, DC 20001

Dr. W. Steve Sellman
OASD(MRA&L)
2B269 The Pentagon
Washington, DC 20301

Dr. Sylvia A. S. Shafto
OERI
555 New Jersey Ave., NW
Washington, DC 20208

Dr. T. B. Sheridan
Dept. of Mechanical Engineering
MIT
Cambridge, MA 02139

Dr. Ben Shneiderman
Dept. of Computer Science
University of Maryland
College Park, MD 20742

Dr. Ted Shortliffe
Computer Science Department
Stanford University
Stanford, CA 94305

Dr. Lee Shulman
Stanford University
1040 Cathcart Way
Stanford, CA 94305

Dr. Randall Shumaker
Naval Research Laboratory
Code 7510
4555 Overlook Avenue, S.W.
Washington, DC 20375-5000

Dr. Robert S. Siegler
Carnegie-Mellon University
Department of Psychology
Schenley Park
Pittsburgh, PA 15213

Dr. Herbert A. Simon
Department of Psychology
Carnegie-Mellon University
Schenley Park
Pittsburgh, PA 15213

LTCOL Robert Simpson
Defense Advanced Research
Projects Administration
1400 Wilson Blvd.
Arlington, VA 22209

Dr. Zita M Simutis
Instructional Technology
Systems Area
ARI
5001 Eisenhower Avenue
Alexandria, VA 22333

Dr. H. Wallace Sinaiko
Manpower Research
and Advisory Services
Smithsonian Institution
801 North Pitt Street
Alexandria, VA 22314

Dr. Derek Sleeman
Stanford University
School of Education
Stanford, CA 94305

Dr. Charles F. Smith
North Carolina State Univers
Department of Statistics
Raleigh, NC 27695-8703

Dr. Edward E. Smith
Bolt Beranek & Newman, Inc.
50 Moulton Street
Cambridge, MA 02138

Dr. Linda B. Smith
Department of Psychology
Indiana University
Bloomington, IN 47405

Dr. Alfred F. Smode
Senior Scientist
Code 07A
Naval Training Systems Center
Orlando, FL 32813

Dr. Richard E. Snow
Department of Psychology
Stanford University
Stanford, CA 94306

Dr. Elliot Soloway
Yale University
Computer Science Department
P.O. Box 2158
New Haven, CT 06520

Dr. Richard Sorensen
Navy Personnel R&D Center
San Diego, CA 92152-6800

Dr. Kathryn T. Spoehr
Brown University
Department of Psychology
Providence, RI 02912

James J. Staszewski
Research Associate
Carnegie-Mellon University
Department of Psychology
Schenley Park
Pittsburgh, PA 15213

Dr. Marian Stearns
SRI International
333 Ravenswood Ave.
Room B-S324
Menlo Park, CA 94025

Dr. Robert Sternberg
Department of Psychology
Yale University
Box 11A, Yale Station
New Haven, CT 06520

Dr. Albert Stevens
Bolt Beranek & Newman, Inc.
10 Moulton St.
Cambridge, MA 02238

Dr. Paul J. Sticha
Senior Staff Scientist
Training Research Division
HumRRO
1100 S. Washington
Alexandria, VA 22314

Dr. Thomas Sticht
Navy Personnel R&D Center
San Diego, CA 92152-6800

Dr. David Stone
KAJ Software, Inc.
3420 East Shea Blvd.
Suite 161
Phoenix, AZ 85028

Cdr Michael Suman, PD 303
Naval Training Systems Cente
Code N51, Comptroller
Orlando, FL 32813

Dr. Hariharan Swaminathan
Laboratory of Psychometric a
Evaluation Research
School of Education
University of Massachusetts
Amherst, MA 01003

Mr. Brad Sympson
Navy Personnel R&D Center
San Diego, CA 92152-6800

Dr. John Tangney
AFOSR/NL
Bolling AFB, DC 20332

Dr. Kikumi Tatsuoka
CERL
252 Engineering Research
Laboratory
Urbana, IL 61801

Dr. Martin M. Taylor
DCIEM
Box 2000
Downsview, Ontario
CANADA

Dr. Perry W. Thorndyke
FMC Corporation
Central Engineering Labs
1185 Coleman Avenue, Box 580
Santa Clara, CA 95052

Major Jack Thorpe
DARPA
1400 Wilson Blvd.
Arlington, VA 22209

Dr. Douglas Towne
Behavioral Technology Labs
1845 S. Elena Ave.
Redondo Beach, CA 90277

Dr. Amos Tversky
Stanford University
Dept. of Psychology
Stanford, CA 94305

Dr. James Tweeddale
Technical Director
Navy Personnel R&D Center
San Diego, CA 92152-6800

Dr. Paul Twohig
Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

Headquarters, U. S. Marine Corps
Code MPI-20
Washington, DC 20380

Dr. Kurt Van Lehn
Department of Psychology
Carnegie-Mellon University
Schenley Park
Pittsburgh, PA 15213

Dr. Beth Warren
Bolt Beranek & Newman, Inc.
50 Moulton Street
Cambridge, MA 02138

Dr. David J. Weiss
N660 Elliott Hall
University of Minnesota
75 E. River Road
Minneapolis, MN 55455

Roger Weissinger-Baylon
Department of Administrative
Sciences
Naval Postgraduate School
Monterey, CA 93940

Dr. Donald Weitzman
MITRE
1820 Dolley Madison Blvd.
MacLean, VA 22102

Dr. Keith T. Wescourt
FMC Corporation
Central Engineering Labs
1185 Coleman Ave., Box 580
Santa Clara, CA 95052

Dr. Douglas Wetzel
Code 12
Navy Personnel R&D Center
San Diego, CA 92152-6800

Dr. Barbara White
Bolt Beranek & Newman, Inc.
10 Moulton Street
Cambridge, MA 02238

LCDR Cory deGroot Whitehead
Chief of Naval Operations
OP-112G1
Washington, DC 20370-2000

Dr. Michael Williams
IntelliCorp
1975 El Camino Real West
Mountain View, CA 94040-2216

Dr. Hilda Wing
Army Research Institute
5001 Eisenhower Ave.
Alexandria, VA 22333

A. E. Winterbauer
Research Associate
Electronics Division
Denver Research Institute
University Park
Denver, CO 80208-0454

Dr. Robert A. Wisher
U.S. Army Institute for the
Behavioral and Social Sciences
5001 Eisenhower Avenue
Alexandria, VA 22333

Dr. Martin F. Wiskoff
Navy Personnel R & D Center
San Diego, CA 92152-6800

Dr. Merlin C. Wittrock
Graduate School of Education
UCLA
Los Angeles, CA 90024

Mr. John H. Wolfe
Navy Personnel R&D Center
San Diego, CA 92152-6800

Dr. Wallace Wulfeck, III
Navy Personnel R&D Center
San Diego, CA 92152-6800

Dr. Joe Yasatuke
AFHRL/LRT
Lowry AFB, CO 80230

Dr. Masoud Yazdani
Dept. of Computer Science
University of Exeter
Exeter EX4 4QL
Devon, ENGLAND

Major Frank Yohannan, USMC
Headquarters, Marine Corps
(Code MPI-20)
Washington, DC 20380

Mr. Carl York
System Development Foundation
181 Lytton Avenue
Suite 210
Palo Alto, CA 94301

Dr. Joseph L. Young
Memory & Cognitive
Processes
National Science Foundation
Washington, DC 20550

Dr. Steven Zornetzer
Office of Naval Research
Code 1140
800 N. Quincy St.
Arlington, VA 22217-5000

Dr. Michael J. Zyda
Naval Postgraduate School
Code 52CK
Monterey, CA 93943-5100

ATE

LMED

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